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SUN SENSOR CALIBRATION FOR THE CALIBRATED ORBITING OBJECTS PROJECT (COOP)

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Technical Note

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14. ABSTRACT
This Technical Note describes the calibration of the coarse and medium sun sensors for the Calibrate Orbiting Objects Project (COOP). The data presented will be used by the satellite contractor for Attitude Determination and Control (ADC). The coarse sensors were calibrated at 15° increments along orthogonal axes within its 120° field of view (FOV) and the medium sensors were calibrated at 10° increments along orthogonal axes within its 60° FOV. Step size was reduced to 2° increments between -10° and +10° increase calibration resolution near maximum voltage output. Sensor performance as a function of temperature variance is also characterized for the expected operating range (5C to 69C).

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1.0 SUMMARY

Sensors mounted on the sides and base of a spinning satellite need to be calibrated: two Coarse Sun Sensors (CSS) located on opposing sides and a Coarse and Medium Sun Sensor (MSS) located on the base along with a solar array. The data will be used by the contractor in charge of Attitude Determination and Control Software (ADCS) to enable the satellite to determine attitude relative to the Sun based on voltage readings.

The voltage of the CSS's single diode was tested at 15° increments along both axes across its 120° field of view (FOV). The voltage of the MSS's four diodes was tested at 10° increments along both axes across its 60° FOV. The CSS was tested from 5C to 69C to see if sensor performance varied significantly with temperature. Temperature was found to have an inconsequential effect on voltage response.

The goal of the CSS data is to allow ADCS to determine AOI and make attitude adjustments to bring the MSS into view of the Sun. The broad, symmetrical data recorded for the CSS will allow the satellite to point its base in the general direction of the Sun.

The ADCS is then responsible for making minute adjustments to maximize voltage output for the MSS; thus allowing the solar array surrounding it to maximize solar power generation. The data for the four MSS diodes were summed and maximum output was produced near normal to the sensor mounting surface. Further data was taken between -10° and +10° at 2° increments to increase accuracy near maximum voltage output.

Threshold orientation requirements for the mission required 5° of accuracy and the calibration data for the MSS is within 4°.

2.0 INTRODUCTION

2.1 Objective

Calibration data were needed for the AeroAstro Sun Sensors to enable the satellite's ADCS to meet requirements for attitude adjustment allowing the satellite to maximize solar array power generation during sun pointing operations.

2.1.1

To create lookup tables and/or surface functions from the calibration data to enable ADCS to translate sun sensor outputs into angle of incidence (AOI) measurements.

2.1.2

To ensure that sensor performance is not significantly affected by temperature changes within operating range.

2.2 Sun Sensors

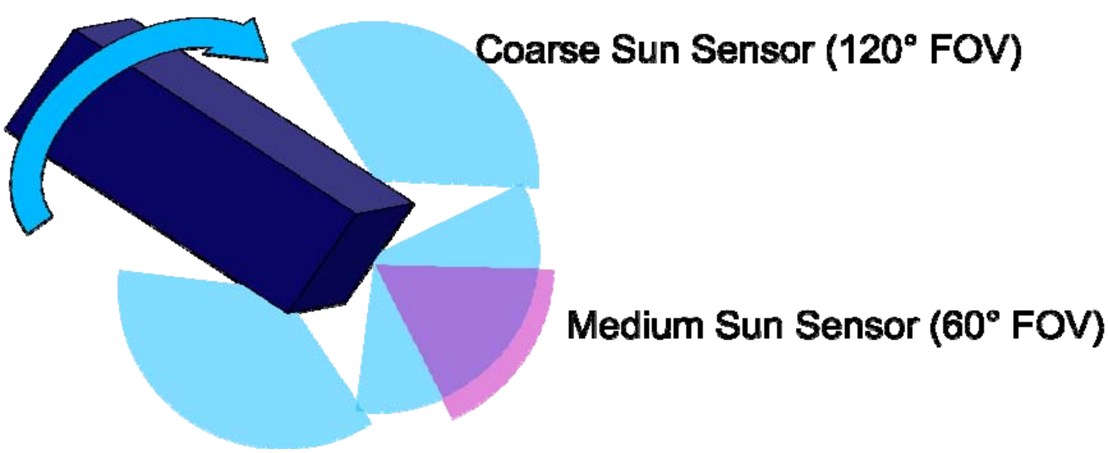
AeroAstro manufactured a Medium Sun Sensor (MSS) and Coarse Sun Sensors (CSS) for use in space. The MSS has a 60° FOV and four solar photodiodes tilted in different quadrants (Figure 1) while the CSS has a 120° FOV and a single photodiode (Figure 2).

Figure 1-Medium Sun Sensor

Figure 2-Coarse Sun Sensor

Two coarse sensors will be mounted on opposing sides of a spinning satellite and a medium and a coarse sensor will be mounted on a third side next to the solar array (Figure 3).

Figure 3-Location of Sensors on Satellite



2.3 Background

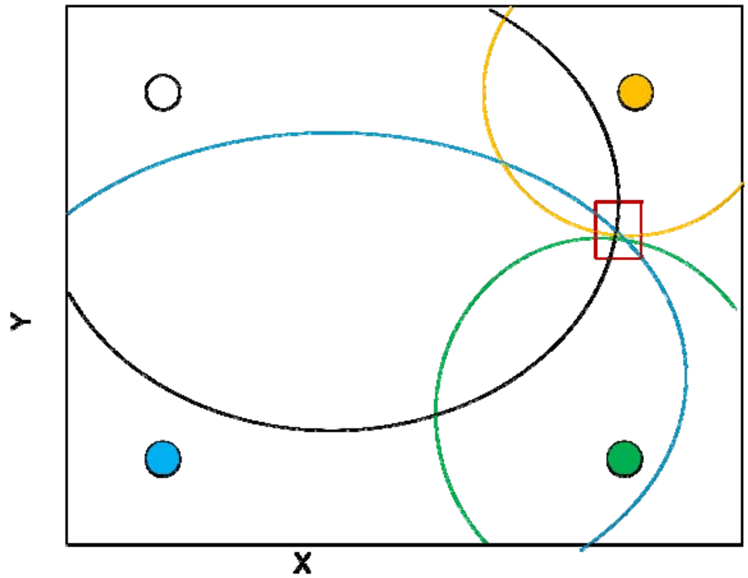
Sun sensors, although mass produced according to listed specifications, contain minute differences in photodiode angles and sensitivities that necessitate calibration for use in space.

The goal of the data from the two CSS which are located along the sides of the satellite is to allow ADCS to determine AOI and make attitude adjustments to bring the MSS into view of the Sun. The AOI was varied at 15° increments because the CSS requires only a coarse view of which direction to turn and then the MSS data will allow for finer adjustments. The CSS data are symmetrical and include voltage outputs that could correspond to either a positive or negative AOI. The FOV of the CSS at the bottom of the satellite overlaps with the FOV of those mounted on opposing sides, telling the ADCS which AOI the voltage corresponds to based on whether or not the CSS at the base shows a voltage output.

The MSS data allows ADCS to make minute attitude adjustments, allowing the adjacent solar array to maximize solar power generation. The threshold orientation accuracy for the satellite is 5°. ADCS required calibration data that would allow for fine adjustment: the data set included 10° increments along the entire FOV and 2° increments surrounding the region normal to the sensor mounting surface.

The MSS has four individual diodes canted towards the sensor's quadrants, each receiving voltage outputs. A potential application of the data is to relate x angle, y angle and voltage by processing calibration data into a 3D surface. By orienting these surfaces to correspond to sensor setup, ADCS could generate contour projections of AOI based on on-orbit voltages. The intersection of these projections would be the satellite's attitude relative to the Sun (Figure 4).

Figure 4-Visual Example Attitude Determination



To capture the necessary calibration data, the sensors were tested using a Calibrated AM0 Sun Simulator light source at varying angles of incidence, recording voltage output from the photodiodes at each position. The sensors were also tested across a range of temperatures to see if there is performance variation within the company's listed temperature range.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Materials

3.1.1 Equipment Under Test

-AeroAstro Coarse Sun Sensor (Appendix A)
-AeroAstro Medium Sun Sensor (Appendix A)

3.1.2 Test Support Equipment

-Spectrosun X-25 Mark II Solar Simulator (Appendix A)
-Re-circulating Heater/Chiller
-Equivalent Operational Circuit
-Digital Volt-Meter/Multi-Meter (DMM)
-Dual-Axis Angular Positioning System
-Level (to ensure a level elevation plane after axial adjustments)
-Positioning Tiles, Blocks, Fasteners
- Balloon Standard (Device sent out of atmosphere to measure the Sun's expected intensity on orbit; used to calibrate solar simulator.)

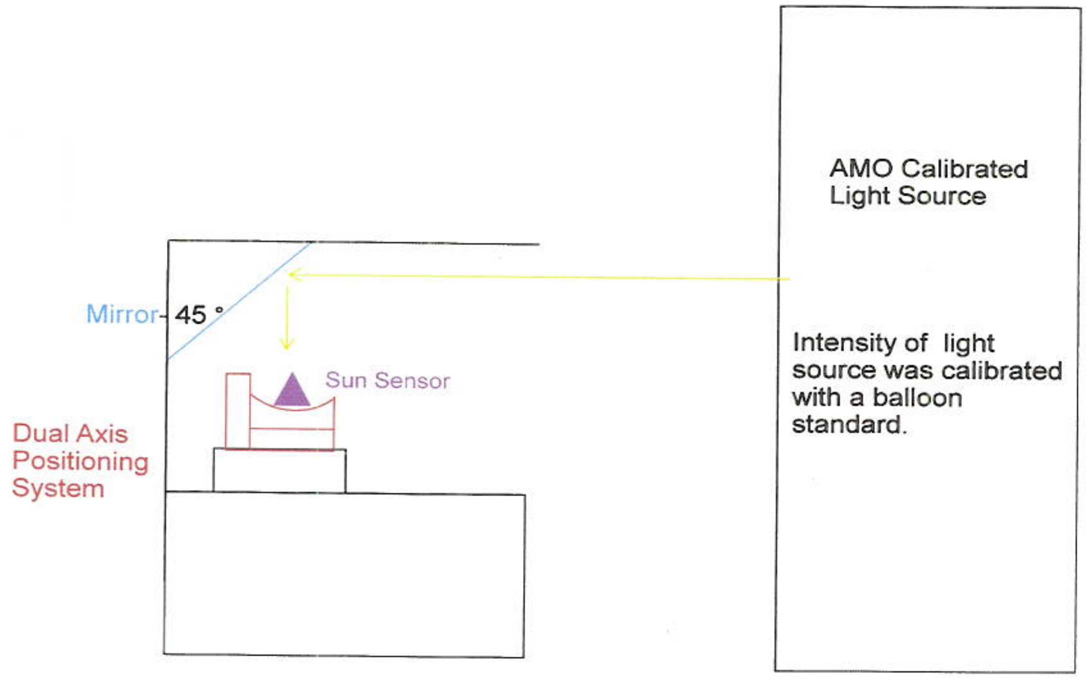
3.2 Setup

3.2.1 Light Source

The light source intensity was AM0 calibrated using a 75 mV Balloon Standard. The standard was connected to the DMM and the intensity was adjusted by varying distance between the light source and setup location until the DMM read 75mV.

The sensor was placed on top of the positioning system and below a mirror angled at 45° (Figure 5). The Solar Simulator has a laser focusing feature which ensured that the light provided power on target.

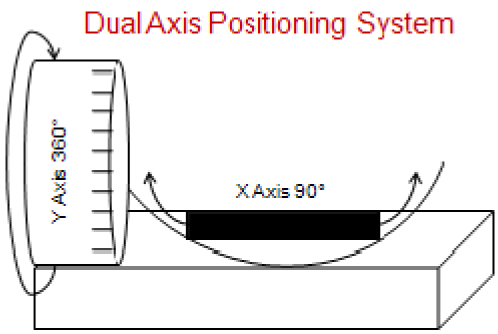
Figure 5-Test Setup



3.2.2 Positioning System

The positioning system required manual adjustment. Error associated with this was minimized by leveling the surface on which the sensor was placed in both directions at the beginning of the test and along the minor axis after each major axis adjustment. The major angular axis (y) was adjusted on the large drum which had an accuracy of 1°. The sensor was placed flush against a table which moved along the minor angular axis (x) that had markings identifying every angle from -45° to +45° and was adjusted using a small knob (Figure 6).

Figure 6-Dual Axis Positioning System



Each sensor was oriented based on physical markings such as bolt holes and lead colors and, for the purposes of this test, x and y axes were assigned (Figure 7 & Figure 8).

Figure 7-CSS Physical Layout

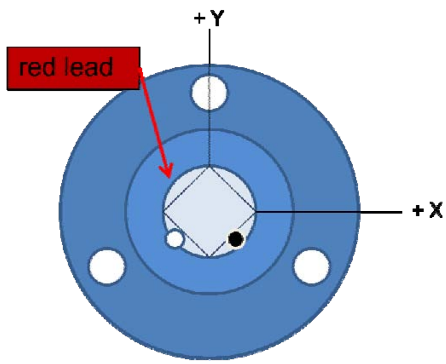
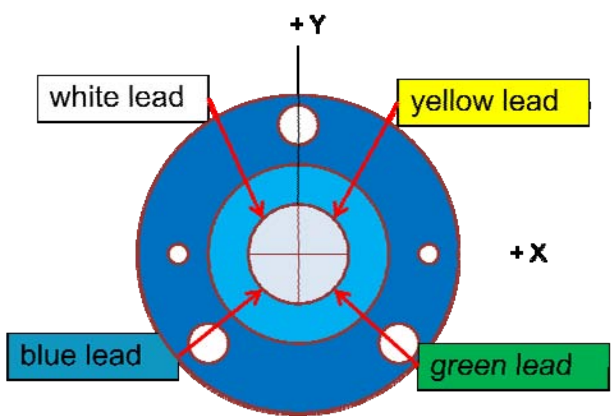


Figure 8- MSS Physical Layout



3.3 Assumptions

3.3.1 Light Source

Beam intensity was assumed stable after calibration (**3.2.1)** based on the Solar Simulator specifications (App A).

After ensuring appropriate positioning (**3.2.1**), it was assumed that the light remained correctly focused.

3.3.2 Positioning System

The x axis was leveled after the y axis was adjusted to a new angle. It was assumed that the positioning system remained level as the x angles were adjusted.

3.3.3 Temperature

The ambient temperature was 30C, well within the -40C to 93C temperature range listed for both sensors. It was assumed that temperature variation of the sensor resulting from exposure to the sun simulator during the test was minimal. (To ensure that this minimal variation did not alter voltage response significantly to affect calibration data, a limited range temperature test was performed [See Sections **3.4.3** & **4.3**]).

3.4 Procedure

3.4.1 Coarse Sun Sensor Angle of Incidence

The major axis was adjusted to the desired angle and then measurements were taken for the range of x angles. This was repeated for each y angle. Voltage readings were taken for the single diode at 15° increments along both axes, from -60° to +60° along the y axis and -45° to +45° along the x axis. The x axis range was limited by constraints of the positioning system used.

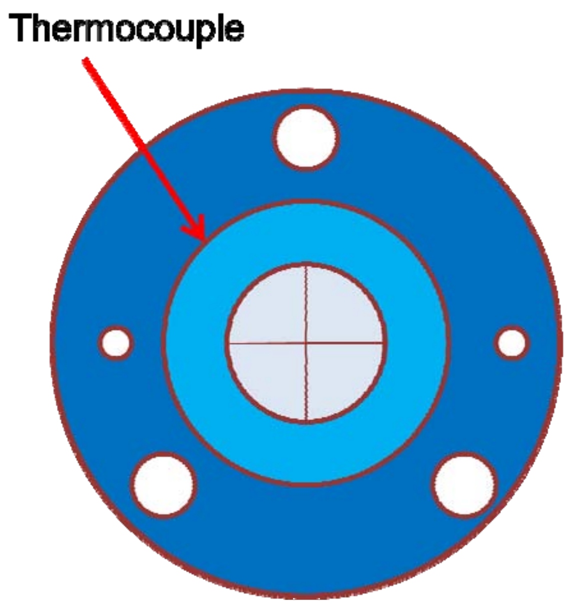
3.4.2 Medium Sun Sensor Angle of Incidence

The major axis was adjusted to the desired angle and then measurements were taken for the range of x angles. This was repeated for each y angle. The MSS was tested at 10° increments from -30° to +30°. Further data was taken at 2° increments from -10° to +10° so finer adjustments can be made towards the center of the sensor.

3.4.3 Limited Range Temperature Test

A thermocouple was placed at the base of the MSS located at angle 0,0 (Figure 9). The sensor was allowed to cool to ambient temperature, being continuously monitored to note the equilibrium temperature. The sun simulator was then turned on and temperature was measured simultaneously with the voltage response of a single diode until the temperature of the sensor under the light source reached equilibrium.

Figure 9-Thermocouple Location



3.4.4 Extended Range Temperature Test

A more comprehensive temperature test was performed to see whether sensor performance varied with a larger range of temperatures such as might be seen on orbit. A thermocouple was attached to the base of the CSS (Figure 9-Thermocouple **Location** to monitor temperature. The CSS was placed at angle (0,0). Using the Heater/Chiller, the sensor temperature was dropped to 5C and then raised to 69C while voltage readings were taken continuously to see if performance was significantly affected.

3.5 Test Chronology

- 06/04/09: CSS- Set 1, MSS- Set 1 (+y values repeated with no –y value measurements taken)

-06/09/09: MSS- Set 1 (-y values), Limited Range Temperature Test

-06/17/09: MSS- Set 2

-06/18/09: MSS- Fine Scale, Extended Range Temperature Test

-07/08/09: CSS- Set 2

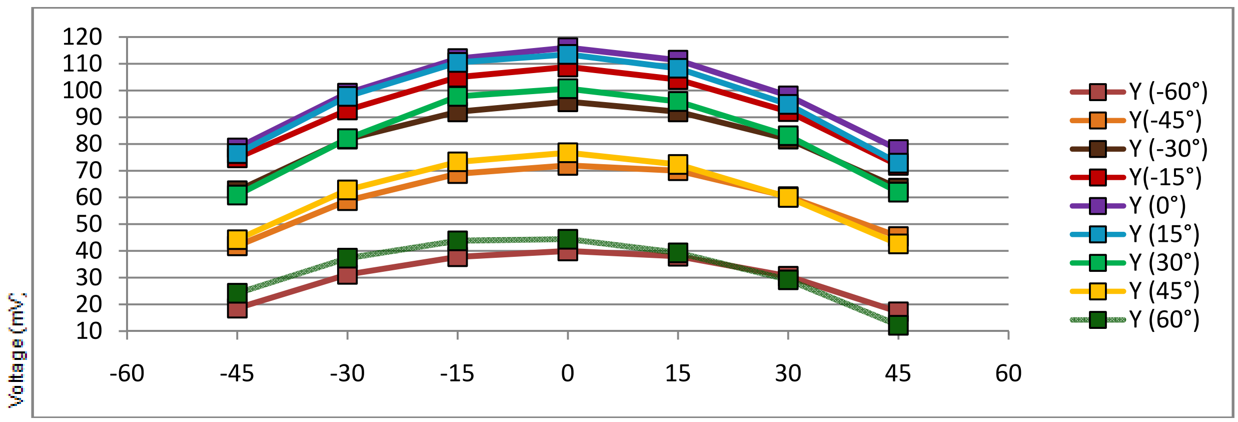
4.0 RESULTS AND DISCUSSION

4.1 Coarse Sun Sensor

4.1.1 Data Set 1

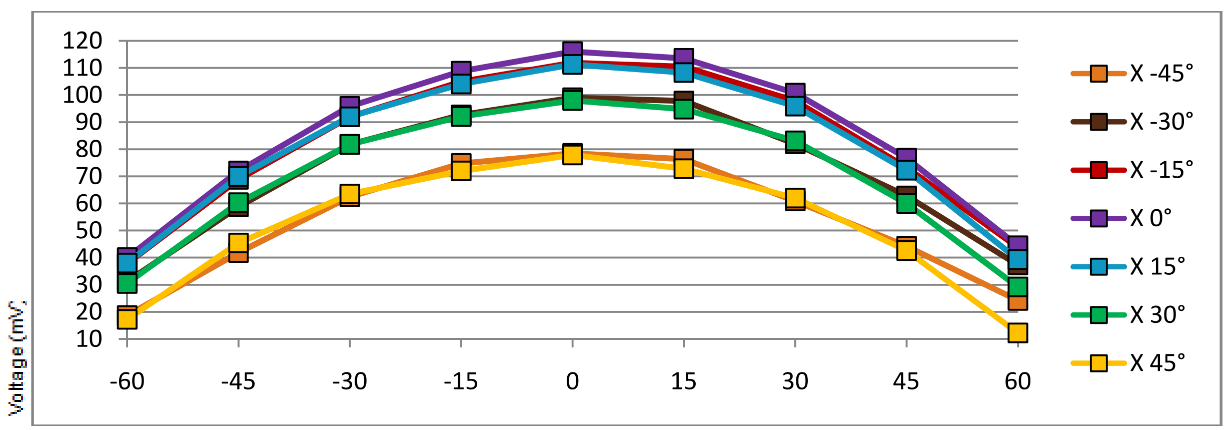
The CSS data was graphed with voltage vs. x angle (Figure 10) and voltage vs. y angle (Figure 11). Voltage vs. x is a more accurate graph because it reflects how the data was actually taken; each line represents an angular variation of the major axis and the data points along the line represent the x angle variations along the minor axis. The paired lines show that the data was symmetrical, as would be expected.

Figure 10- CSS Voltage vs. X Angle: Set 1



X Angle (°)

Figure 11- CSS Voltage vs. Y Angle: Set 1



Y Angle (°)

However, when taking Data Set 1, a light near where the sensor was being tested was unintentionally left on. The voltage readings by the sensor included not only the simulated sunlight but also voltages from the work lights. Likewise, the temperature of the sensor was slightly elevated. This unaccounted for voltage was discovered following the extended range temperature test (see section **4.4**) and the CSS data was retaken to ensure accuracy.

4.1.2 Data Set 2

The second test was performed using the same procedure but the work lights over the sensor were turned off, so all light was coming from the sun simulator. The maximum voltage produced under these conditions was 104mV, very close to the maximum voltage in the temperature test: 103mV (Figure 12 & Figure 13).

Figure 12-CSS Voltage vs. X Angle: Set 2

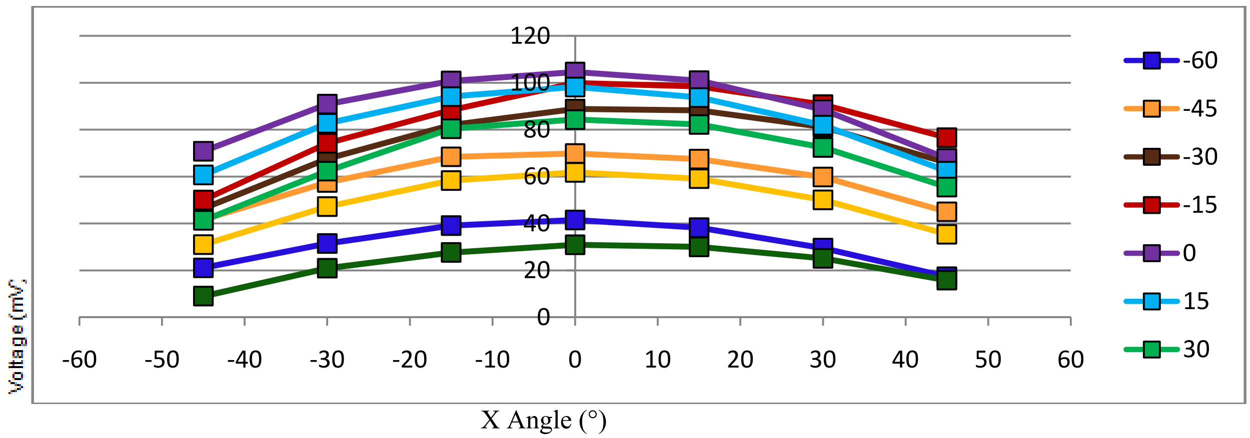
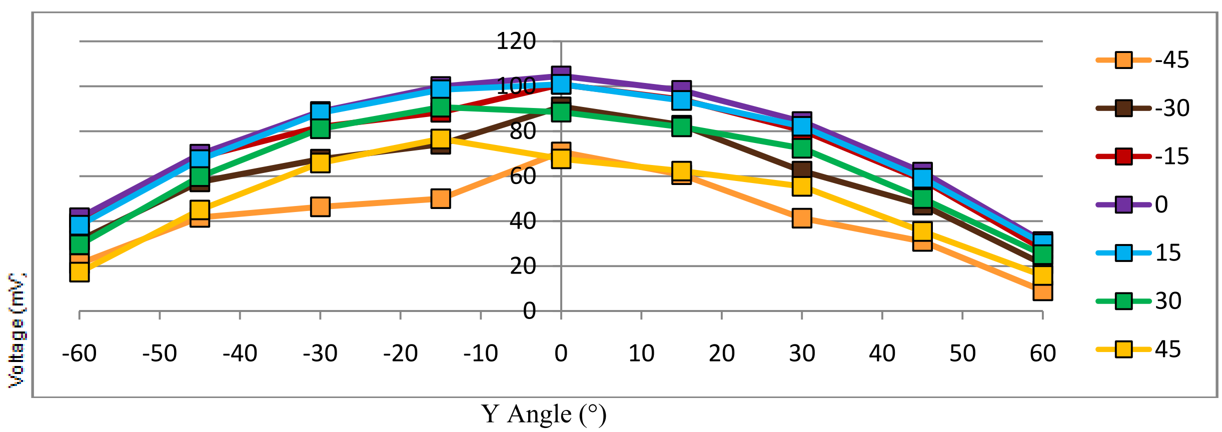


Figure 13-CSS Voltage vs. Y Angle: Set 2



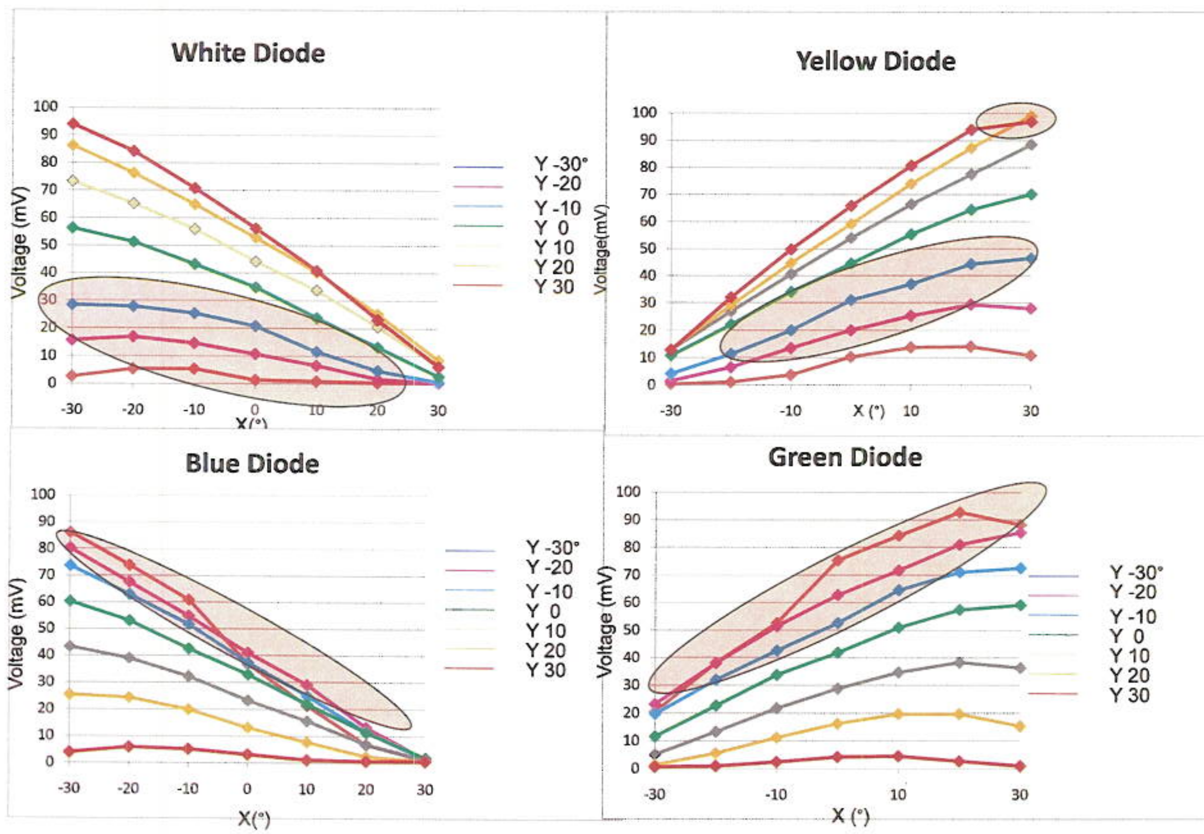
Although the data in Figure 13 appears erratic, the lowest r^2 value was .90. The lines seem less smooth than CSS Set 1; the light over the sensor boosting the voltage output seems to have had an unexpected stabilizing effect on the voltage response.

4.2 Medium Sun Sensor

4.2.1 Data Set 1

The MSS has four photodiodes with differently colored leads. For the purposes of this test, the diodes will be referred to by lead color. The data were graphed with respect to separate diodes so trends would be more readily apparent (Figure 14).

Figure 14- MSS Voltage vs. X: Set 1



Several discrepancies were noted and the incongruent behavior is highlighted in red above. Some data points overlapped making it unclear to which angular position an on orbit voltage reading would correspond. On the first day of testing, the +y values were inadvertently measured twice and the –y values were overlooked. The –y values were taken on a later date and those three –y angles show notably lower voltages on the yellow and white diodes and erratic crossing on the green and blue diodes. The lower voltages suggested for the first time that the work lights over the sensor may have been on. (This was later positively concluded after seeing the discrepancies between CSS Data Set 1 (Figure 10 & Figure 11) and the Extended Range Temperature Test [Figure 20]). All of the r^2 values with a polynomial fit were higher than .95 except for the white and yellow diodes at y=-30: .57 & .86, respectively, and the green and blue

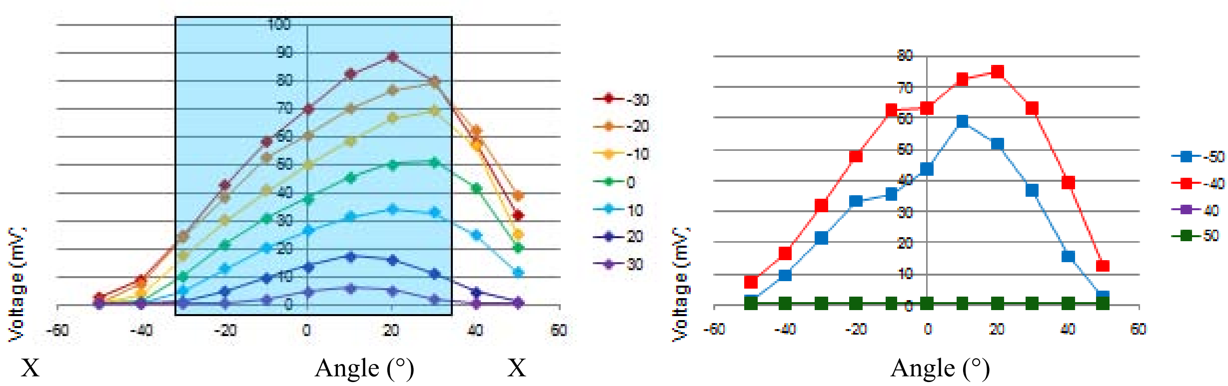
diodes at y=+30: .79 & .77, correspondingly. These low correlations are likely due to the fact that the diodes were receiving very low voltages at these points because they were at high AOI with the sun. It was not known whether the other discrepancies were due to the sensor or the setup, so another data set was taken to ensure accuracy.

4.2.2 Data Set 2: Extended FOV

In the 2nd data set a FOV wider than that stated for the sensor was tested (Figure 15). A full data set was desired so that a full surface could be plotted for each diode. Using only the listed FOV gave an incomplete data set from which to extrapolate the curve. This test would also show whether voltage readings outside of this range could provide useful calibration data to ADCS.

Figure 15-Green Diode Extended FOV

Listed Y Angles **Extended Y Angles**

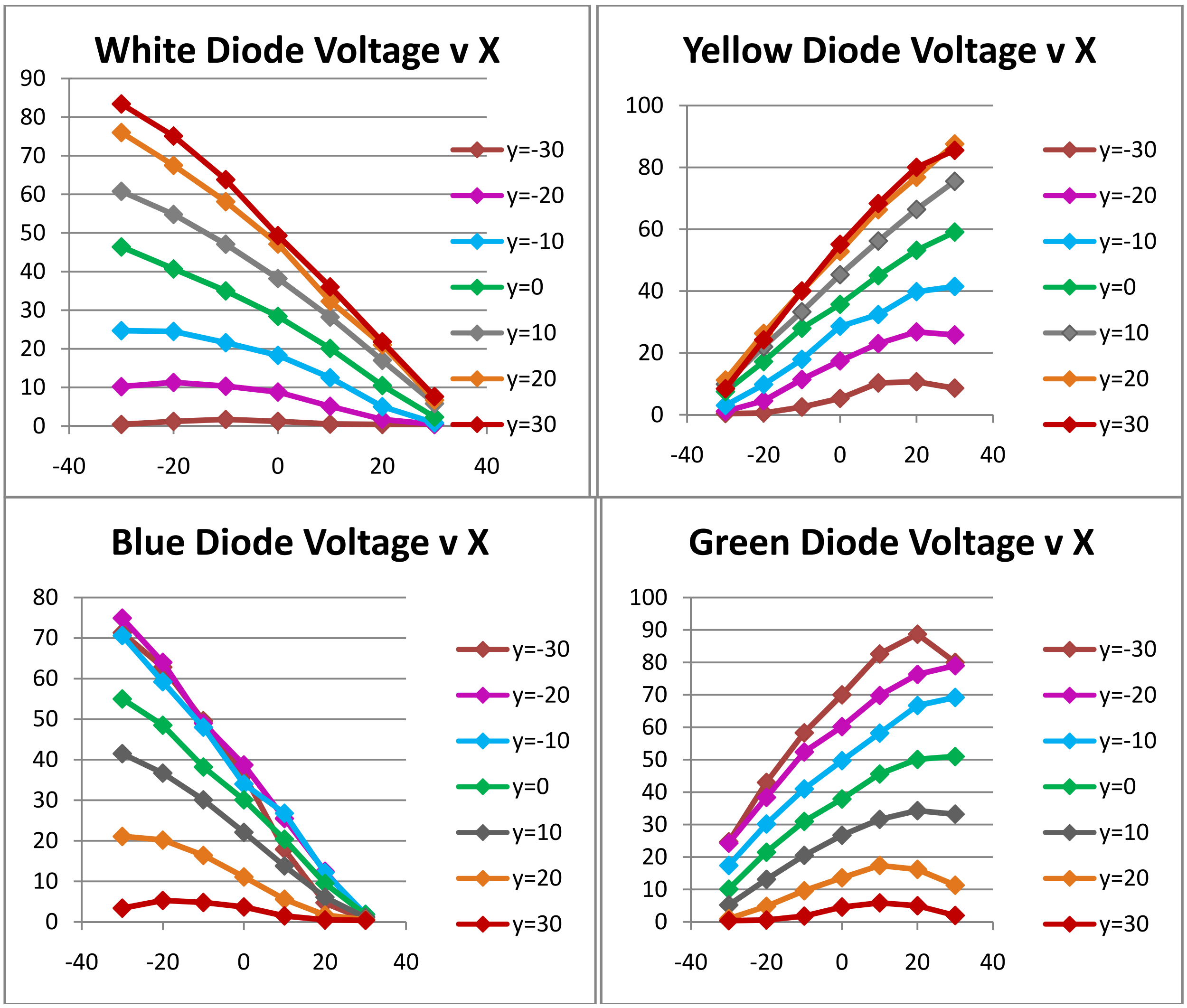


As intended, the extended FOV cleared up ambiguity about the behavior of the sensors and provided a full data set. However, outside of the listed FOV the voltage response was either erratic or inconsequential. The listed y angles (Figure 15) on the left show that the data set was filled out by testing the Extended FOV; however, the data drops off quickly with significant overlapping. Using a polynomial fit, the r^2 values for these curves were low: a high of .91, a low of .49 and a median of .83. The listed range of x angles are highlighted in blue and fitting the curves within these bounds gives five r^2 values of .98 and higher. The angles with the lowest r^2 values were 20° & 30°: .93 & .72 respectively. These low values are understandable in light of the fact that the lowest correlations for both the MSS and CSS have been when the sensor is at a high AOI with the light source and receiving low voltage. The extended y angles (Figure 15) did not produce a consistent response: inconsequential readings at +y AOI and poor trends at the –y AOI. Due to the inconsistency of data outside the listed FOV, only the voltages corresponding to angles within the sensor's parameters were considered usable as calibration data.

4.2.3 Data Set 2

The second set of data indicated that there had been a change in the setup (presumed to be the work lights left on during the first day of testing) over the two days Data Set 1 was taken because the data taken in a single day did not show a voltage drop between groups of data (Figure 16).

Figure 16- MSS Voltage vs. X Angle: Set 2



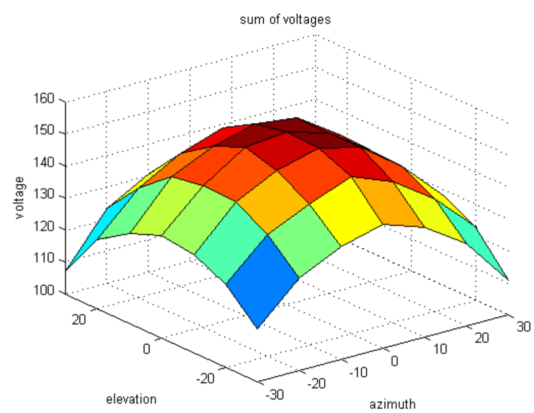
MSS Set 2 also showed that the overlapping of data points at high AOI was a characteristic of the sensor and not an inconsistency in the setup. This overlapping is due to the parabolic voltage response of the sensor. The extended FOV data (Figure 15) show that as the y angle changes the peak voltage response for a diode occurs at different x angles; the overlapping at high AOI is due

to the voltage dropping along the line for one major axis angular variation while rising along the line of another.

4.2.4 MSS Maximum Voltage

Using Matlab, the surfaces for the 4 individual diodes were summed to find an AOI near which the voltage output was maximized (**Figure** 17).

Figure 17-Sum of Diodes



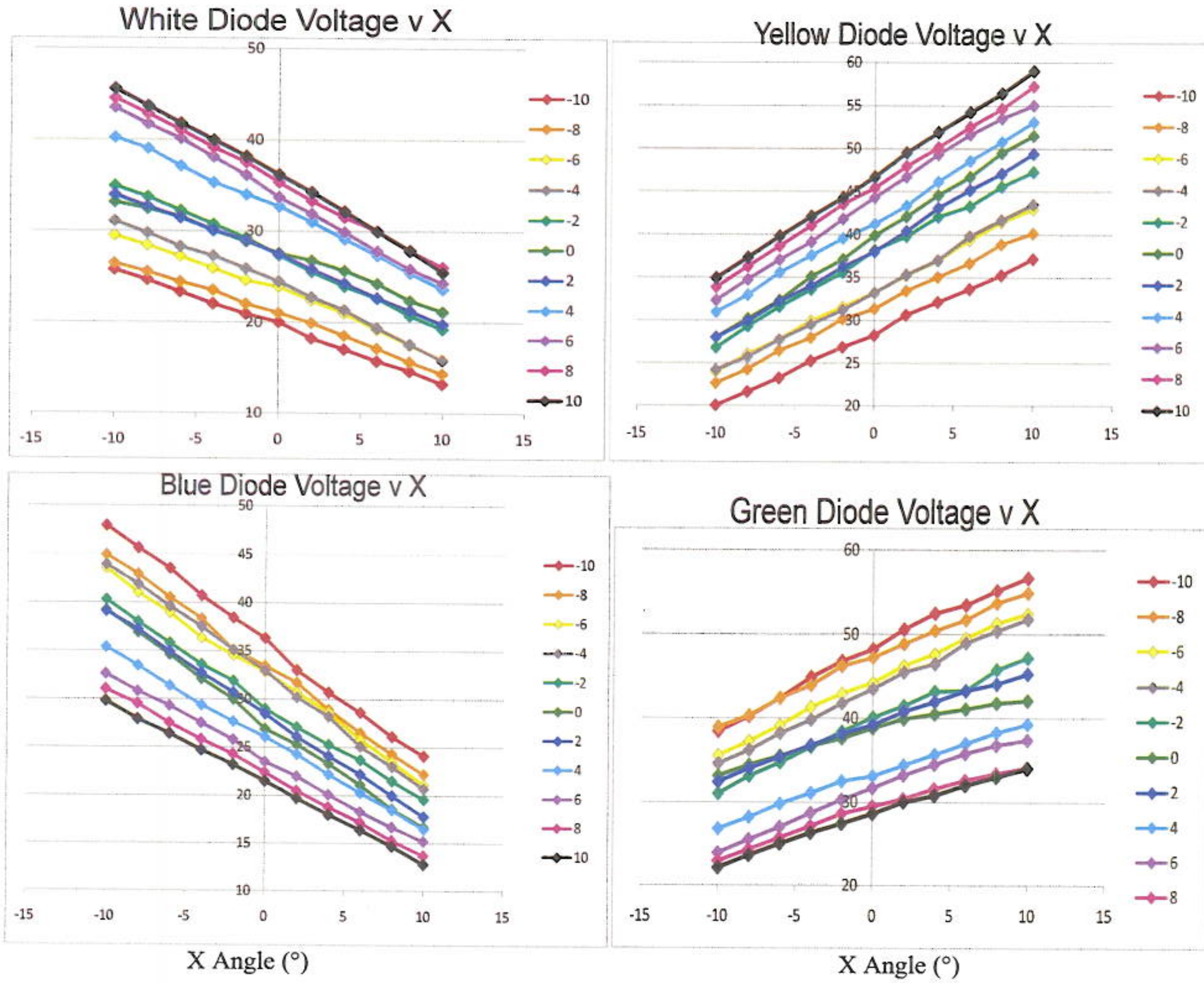
The maximum voltage output was somewhere near normal to the sensor mounting surface, so a finer set of data was taken between -10° & +10° at 2° increments (

Table **1** & Figure 18).

Table 1-Example of Fine Scale Voltages: Blue Diode

Blue	X Angle			MSS							
Y Angle	-10	-8	-6	-4	-2	0	2	4	6	8	10
-10	47.9	45.6	43.5	40.7	38.4	36.3	33	30.7	28.6	26.1	24.1
-8	44.9	42.9	40.5	38.3	35.1	33.4	31.7	28.9	26.5	24.3	22.2
-6	43.5	41	38.9	36.3	34.5	32.8	30.7	28.6	25.8	23.5	21.1
-4	43.9	41.9	39.6	37.5	35.1	33	30.2	28.2	25.1	23	20.7
-2	40.3	38	35.8	33.6	31.9	29	27.1	25.3	23.7	21.5	19.6
0	39.2	36.9	34.6	32.1	30	26.9	25.3	23.3	21.1	18.6	16.7
2	39.1	37.2	34.9	32.7	30.7	28.5	26.1	24.1	22.2	20	17.8
4	35.4	33.5	31.4	29.4	27.7	26.1	24.3	22.2	20.3	18.5	16.5
6	32.6	30.8	29.3	27.5	25.8	23.5	22	20.1	18.3	16.7	15.2
8	31	29.5	27.5	25.8	24.3	22.4	20.5	18.8	17.2	15.3	13.7
10	29.8	27.9	26.4	24.7	23.2	21.5	19.7	18	16.4	14.7	12.8

Figure 18- MSS Voltage vs. X Angle: Fine Scale

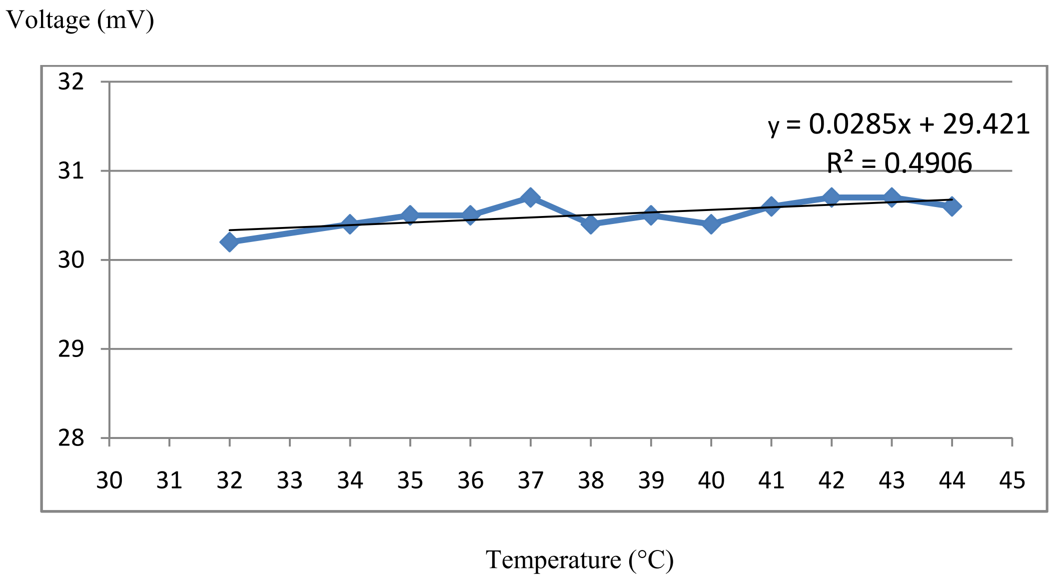


The finer data all showed r^2 values of .99 but there was some overlapping of the middle three angles, from -2° to +2°. The threshold orientation accuracy requirement for the satellite is 5°. The calibration data is within 4° of accuracy and is presumably sufficient.

4.3 Limited Range Temperature Test

This test was performed to ensure that the minimal temperature variations that resulted from exposure to the light source over the course of the test did not affect the voltage response significantly to alter the calibration data.

Figure 19- Limited Range Temperature Test



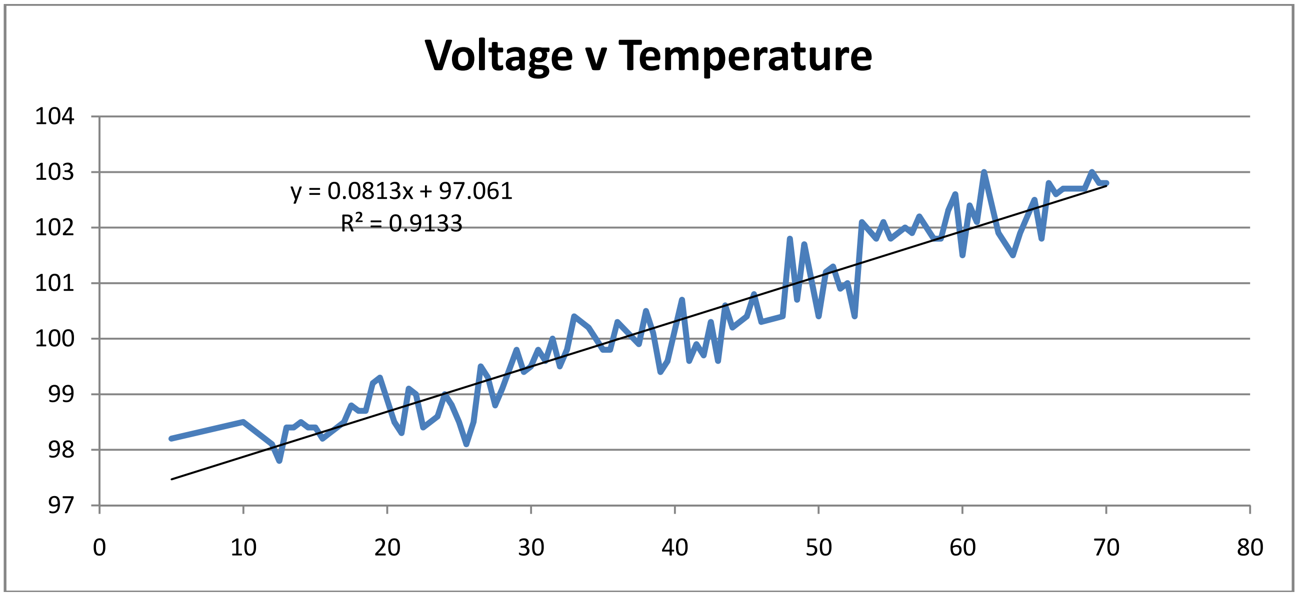
The low r^2 value is an indication of the noise in the reading of the DMM. The range of variation was .5mV as the temperature rose from ambient and reached equilibrium under the sensor. This slight difference was not considered sufficient to cause concern about the validity of the calibration data.

4.4 Extended Range Temperature Test

The listed temperature range for both sensors is -40C to 93C. The limited range temperature test ensured that calibration data was not affected by temperature changes that occurred as the sensor was exposed to the sun simulator for a limited time. A more comprehensive test was necessary to ensure that sensor performance would not be significantly affected by larger temperature variations such as might be seen on orbit (Figure 20).

Figure 20- Extended Range Temperature Test

Voltage (mV)



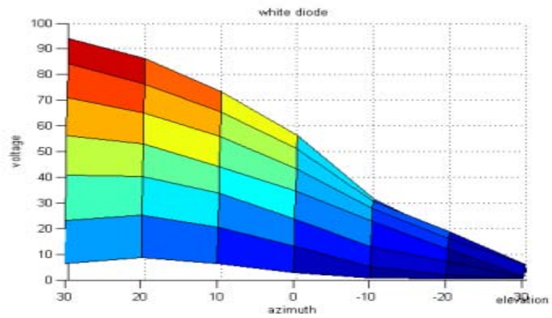
Temperature (°C)

This temperature test showed that with a 70C variation of temperature the voltage response changed only 5mV, an inconsequential amount. This assurance was necessary because if a large voltage response variation was apparent, the satellite would need to monitor temperature of the sensor on orbit to ensure correct operation; these results show that to be unnecessary. The highest voltage reading of the sensor was 103mV, significantly lower than 116mV produced during the CSS Data Set 1 but corresponding closely with CSS Data Set 2 maximum value of 104mV. This correlation gave reasonable assurance that the temperature test and CSS Set 2 were accurate, so an additional temperature test was deemed unnecessary.

4.5 Potential Application of Data

The voltage output the satellite receives from the 3 CSS will allow ADCS to bring the satellite's base toward the Sun, where the MSS data will be used to make minute adjustments. The calibration data for each diode was processed using Matlab to create a 3D surface (Figure 21).

Figure 21-White Diode Surface



The ADSC will receive 4 simultaneous voltage readings from the MSS (Table 2).

Table 2-Example of On Orbit Reading

Diode	Voltage (mV)
Blue	11.4
Green	57.3
Yellow	64.3
White	13.2

By orienting the surfaces of each diode similar to the sensor and using the voltage readings, contour projections can be generated giving x and y angular positions for each diode (Figure 4). The intersection of these projections will be the satellite's attitude relative to the Sun.

5.0 CONCLUSIONS

5.1 Conclusions

The calibration of the CSS and MSS was successful. The data for both sensors was taken twice and the data showed a high correlation. The threshold orientation accuracy was 5° and the calibration data has within 4° of accuracy. The listed FOV was tested and found to be accurate, data outside those limits being inconsistent. A 70C temperature range was also tested and the performance of the sensor was not significantly affected, this range being well within the listed -40C to 93C.

5.2 Applications

The calibration data will be used by the contractor in charge of ADCS. The data will be used to control attitude adjustment during passive, sun pointing operations. On orbit voltage readings will be compared to the calibration data and will allow ADCS to determine the satellite's AOI with respect to the Sun. The satellite will then turn until the solar array faces the Sun, maximizing solar power generation.

6.0 REFERENCES

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7.0 LIST OF ABBREVIATIONS AND ACRONYMS

ADCS	attitude determination and control software
AOI	angle of incidence
CSS	Coarse Sun Sensor
DMM	Digital Volt-Meter/Multi-Meter
FOV	field of view
MSS	Medium Sun Sensor

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